Immersive VR Environments, Full Body Tracking and Digital Human Models for Ergonomic Validation of Maritime Patrol Aircraft's Interiors

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***Abstract*—In this paper, a human-centered design methodology is proposed to support the interiors design of a Maritime Patrol Aircraft (MPA). The combined use of Immersive Virtual Reality (VR) tools and Digital Human Models (DHMs) are exploited to include both objective and subjective measurements in the ergonomic evaluation process. The main issue consisted in defining the optimal ergonomic design configuration for Operator Console Area and Observer Window Area of MPA's digital mock-up, provided by Leonardo S.p.A. The methodology is based on a five-step iteration process: once having identified the requirements, required input data and the design variables, the ideated configuration is evaluated using DHMs in order to retrieve objective measurements (i.e., interferences, visibility, reachability); finally, a subjective assessment within immersive VR environment is conducted. A real-time RULA analysis is carried out on DHMs, calibrated on selected users representing specific percentages of target population, by means of a full-body tracking system. The subjective assessment in immersive VR allows to take into account also other human factors (i.e. human ability, dexterity and cognitive aspects) that have not been previously considered and may significatively influence the validation of the final design configuration of MPA interiors.**

Keywords*—*Digital Human Modeling, Digital Mock-up, Virtual Reality, Ergonomic Validation, Maritime Aircraft

I. Introduction

Ergonomics is an essential principle in the manufacturing process, since it analyses the connection between physical aspects of humans and workplaces, including human anthropometry, physiology, anatomy, and biomechanics, among other factors [1, 3, 16, 17]. As a result, everything in the workplace (seat, tools, devices, items to be handled, etc.) must be designed in such a manner that a worker is able to execute activities with efficient motions, using minimal energy, with low and mitigated risk of injury [2, 3]. In this context, Digital Mock-Ups (DMUs) and Digital Human Models (DHMs) can be used to simulate and optimize human performances in advance before the creation of a plant, a machine or an aircraft [4]. The use of DHM may lead to improve physical product ergonomics and reduce the need for building physical prototypes [7, 19]. Furthermore, the use of Virtual Reality (VR) can help to improve the realism and effectiveness of virtual simulations by supplementing the constraints in the use of DHM to assess physical ergonomics and the need of including subjective aspects in the ergonomic evaluation process [18].

Currently, there is still a lack of awareness and knowledge of human factors/ human-centered design methods, even for aircraft industries [9]. For this reason, we propose a human-centered design methodology, based on a five-step iteration process, exploiting VR tools to include both objective and subjective measurements in the ergonomic evaluation process.

In this work, the proposed methodology (described in Sect. II) is applied to a Maritime Patrol Aircraft case study (Sect. III), kindly provided by Leonardo S.p.A.. After a quick description of the employed Software Hardware equipment in Sect. IV, Sect. V and Sect. VI address, respectively, the application of the proposed methodology on two areas of the MPA: Operator Console Area and Operator Observer Window Area. Finally, conclusions and considerations are given in Sect. VII.

II. Methodology

The adopted methodology is articulated in 5 steps (*A. Requirements identification, B. Input data collection, C. Analysis of variables, D. Virtual Verification, E. Ergonomic Validation in immersive environment*). As showed in Fig.1, the first stage consists in identifying the requirements that must be fulfilled for the specific case study. In the second stage, the required input data is gathered; in the third, the analysis of the variables (intended as the design parameters that can be modified, if necessary, to evaluate alternatives to the current concept, in order to meet all the requirements) is conducted. In the fourth and fifth phases, the ergonomic verification and validation of the concept within VR environment are made. First, third-person virtual mannequins (DHMs), according to the human percentile reference values, are employed to evaluate the objective ergonomic aspects (i.e., interferences, visibility, reachability). If the tested concept results not to be compliant with any requirements for one or more percentiles, it is necessary to formulate and test again an alternative solution, acting on one of the variables previously identified. Once having fulfilled all the requirements, the fifth step of the methodology is executed. For each selected percentile of the target population, users are asked to execute typical tasks (seat, stand up, look at the screen, try to reach all the buttons of the console, look out the window, etc.), while being immersed within the MPA in-scale mock-up.

A full-body tracking system is employed to calibrate the users and their DHMs, in order to conduct real-time RULA[1] analyses while operating within the immersive VR environment. For each user of each percentile, the worst RULA scores are registered. Then, mean values of RULA scores are calculated and compared to the reference values (Fig.2) to validate (or not) the design configuration of MPA interiors. In particular, RULA scoring system is employed to assess the risk of musculoskeletal loading within the upper limbs and neck related to the workplace design concept, in order to retrieve different levels of urgency of investigation [6] of such ergonomic configuration.

As the previous step, if the requirements are met for all the testers, the concept is validated. However, if at least one human percentile obtains a RULA score >6, the concept cannot be validated and an alternative solution must be formulated, acting on one of the variables previously identified. In this way, the concept is iteratively tested with *D.* and *E.* steps, up to the validation of the proper alternative configuration. In addition to the previous step, virtual test in immersive VR environment and real-time RULA analysis allow to introduce a subjective assessment in the ergonomic evaluation process, highlighting human factors (as cognitive, stress aspects, etc.) that have not been previously taken into account and may significatively influence the decisions about the final concept design.

III. Case study: Maritime Patrol Aircraft

The selected patrol boat is a Maritime Patrol Aircraft (MPA), intended to perform Search And Rescue (SAR) missions lasting 8-10 hours. It will host eight crew members: two pilots, four operators at the Operator Console Area and two observers seated at the Observer Window Area. The current design of these areas' interiors has been analysed from the ergonomic perspective. Console Operator Area, which is in the front of the aircraft, is occupied on the right side by the row of the four consoles called Maintenance Operations Control (MOC): the heart of the aircraft mission system, which host four crew members. On the other hand, the Observer Area includes two observation seats (for two crew members) with bubble windows at the aircraft rear.

Premises

Some hypotheses and assumptions were made for design and virtual evaluations:

- The seats are adjustable. Backrest and armrest are reclinable, and the front cushion can be adjusted to the height of the thigh support. Seat Reference Point (SRP) have been used as characteristic point to obtain all the measurements.
- The operator's boots and clothing have a thickness of 25 and 20mm respectively.
- The selected percentiles are 5%, 50%, 95%ile male and 5%ile female, referred to DHMs of American nationality without clothing (Fig.3). The employed reference specification is DEF STAN 00-25 [8].
- For the ergonomic validation within immersive VE, a sample of 3 people was chosen for each percentile, for a total of 12 participants.

IV. Software and Hardware Architecture

Catia V5 software by Dassault Systèmes was used for the objective ergonomic analyses of the work areas. Catia V5 is a parametric CAD software, organised in numerous workbenches that allow its use in almost all stages of the product development cycle. "Mechanical Design" and "Ergonomics Design & Analysis" tools were used in this work. Ergonomic analyses with DHMs were carried out in the "Human Builder" module, to evaluate the reachability, accommodability and available spaces of the selected areas.

The fifth step of the proposed methodology was conducted within the immersive VR environment of IC.IDO [12], an industrial software produced by ESI Group. It provides for a direct CAD converter with Catia and a series of pre-established functionalities for navigation in the virtual environment (Teleport, Fly, Grab World). IC.IDO 's "Ergonomics RAMSIS" [13] module has been mainly employed for the last phase of the proposed methodology. This module allows to easily insert DHMs in the scene, with editable characteristics (height, build, nationality, etc.). The added value offered by IC.IDO compared to the analysis conducted in Catia is the possibility of having a subjective assessment, by conducting real-time RULA analyses on the DHMs.

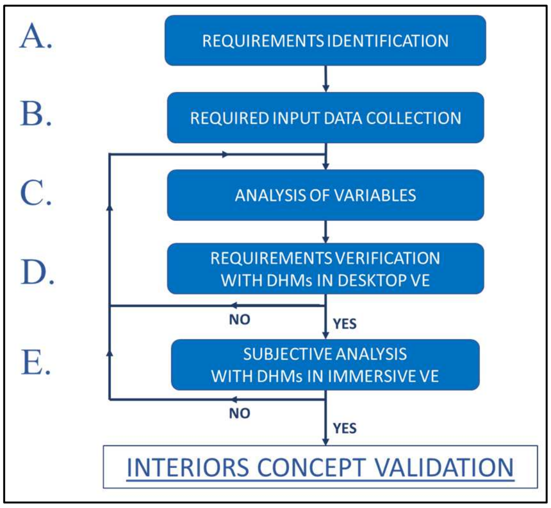

Fig. 1. Five steps of the proposed methodology

Score	Level of MSD Risk
1-2	neglibible risk, no action required
3-4	low risk, change may be needed
5-6	medium risk, further investigation, change soon
6+	very high risk, implement change now

Fig. 2. RULA scoring system

[1] RULA: Rapid Upper Limb Assessment is one of the most employed posture-targeting methods for rapid assessment of risks, allowing for the investigation of work-related Musculoskeletal Disorders (MSD), in particular upper limb disorders [5].

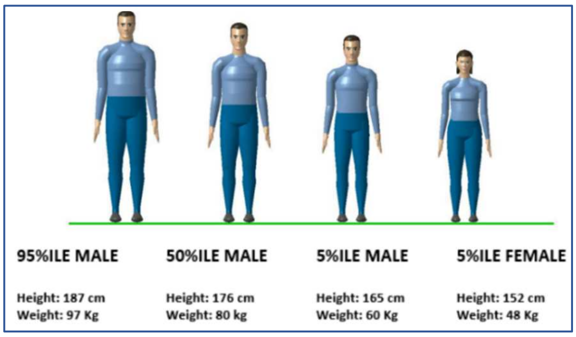

Fig. 3. Percentiles chosen for American population

For the last step of the methodology, users were fully immersed with an in-scale digital mock-up of the MPA, by wearing a full-body tracking hardware system. In particular, we employed the HTC Vive Pro VR system [14], the Manus Haptic Prime II gloves [15] as input devices and 5 VIVE trackers [10] to track respectively the users' hands, the belly and the feet. Tracking data was sent by VIVE hardware equipment to Steam VR [11], which processed and transmitted the data to IC.IDO. In this way, after a quick physical-digital calibration, the user's movements was reproduced in real-time by the respective DHM within the VE. Furthermore, we chose to use a glove-based input system to track also the individual fingers' movements, to have a more precise measurement of the working area in terms of the reachability of each item and button of the console.

V. Ergonomic Validation of Console Operator Area

The objective of this case study was to carry out an ergonomic evaluation of the console space, to verify the correct visibility of the screens and the reachability of the control panels and the oxygen mask (Fig.4).

A. Requirements identification

For this case, it was necessary to verify the seats' suitability (guaranteeing the perfect support of the feet on the ground to the various percentiles), the space available to operators to carry out their activities and the space required for the handling of the seat during take-off and landing of the aircraft. In addition, it was required to verify the visibility of the screens, in order to ensure the right distance between the operator's eyes and the screens on which he works, in compliance with DEF STAN reference 00-25 [8]. For the verification to be validated, the Horizontal line of sight must exceed the minimum limit of 500 mm (Minimum Comfortable Viewing Distance), although a distance greater than 700 mm (preferred comfortable viewing distance) was preferable. Finally, the reachability verification of the main components of the MOC were required: the oxygen mask, the speakers, the joystick, the keyboard, the monitor and the buttons.

B. Input data collection

The following data were required for the study:

- bubble window size and configuration,
- seat dimensions and handling range relative to the SRP position.

C. Analysis of variables

Once having finalised data and requirements, the project variables have been identified. In order to design and evaluate alternative concepts, it was possible to:

1. Change the distance between the seat and the console by modifying seat anchorage point for the same size and configuration of the two components.
2. Change the footprint and configuration of the console and its components.
3. Change the size and range of the seat.
4. Change the console substructure to ensure the operator's accommodation.

D. Virtual Verification

From the ergonomic analysis with DHMs in Catia V5, some issues emerged on the accommodation for 95%ile and 50%ile male (Fig.5: the dummies hit with the knees against the substructure). In this case, it was decided to intervene on variable n.4 (console substructure), to ensure a proper accommodation for all the percentiles. The ideated alternative configuration consisted in introducing a different concept for the crossbar (Fig.6), more streamlined and less bulky than the original. At this point, the objective ergonomic analysis in CatiaV5 was repeated, incorporating the new concepts. Positive results were obtained, since the modified crossbar made it possible to overcome the problem of interference of the knees occurred for 95%ile and 50%ile males, finally guaranteeing a proper accommodation.

E. Ergonomic Validation within immersive environment

A real-time RULA analysis was conducted with the selected users, for each percentile (Fig.7). Users wore the full-body tracking equipment and acted naturally within the VR environment, simulating typical operations at the Console Operator Area.

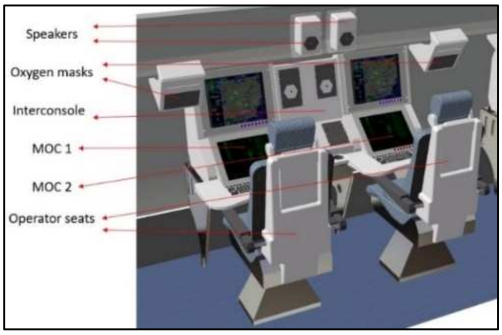

Fig. 4. Layout Console Operator Area

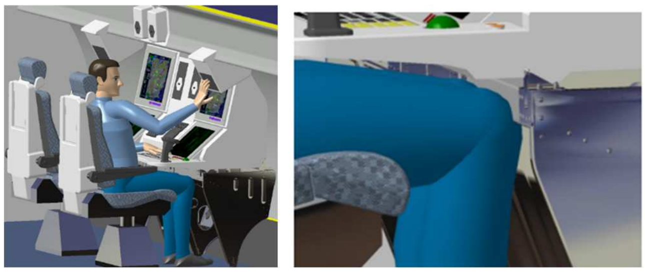

Fig. 5. Reachability verification of Console Operator Area with DHMs. Interference knee-substructure for 95% ile and 50% ile male

Fig. 6. Modified crossbar beam design in the substructure

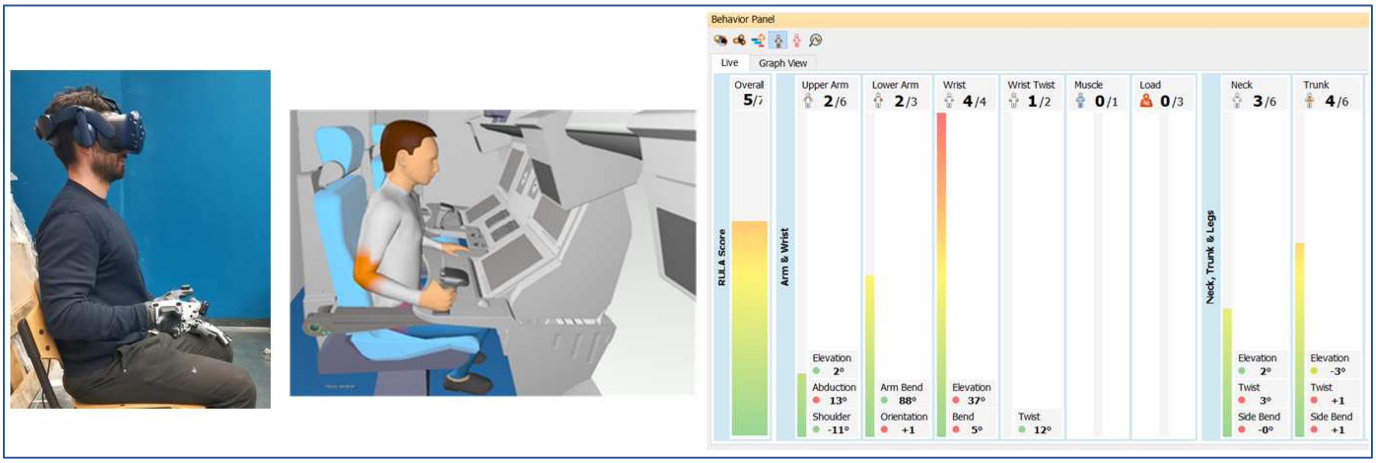

Fig. 7. Peak of detected RULA scores for 50%ile male at Console Operator Area

Percentiles	RULA scores		
	MIN	MAX	MEAN
5% Male	5	5	5
50% Male	4	5	4,6
95% Male	5	5	5
5% Female	4	5	4,3

Fig. 8. Min, max and mean RULA scores registered for all the percentiles at Console Operator Area

An example of the registered data is provided in Fig.7, representing one of the conducted tests for 50%ile male. As expected, the introduction of the new crossbar concepts did not give negative results in terms of interferences. Furthermore, for all the selected percentiles, the most critical action resulted to be the controller grabbing, as it was quite stressful for the users' wrists, given the little space available between the seat and the controller.

For this reason, the RULA scores were registered, and mean values calculated for each percentile. Fig. 8 shows the mean, maximum and minimum values of RULA scores. As can be seen, with reference to the RULA scoring system (Fig.2), the detected level of risk of MSD is between low and medium, still encouraging an iterative approach to modify the current design of Operator Console Area aiming to reduce as possible the stress focused on the operator's wrist. In particular, users affirmed that they would not have been very enthusiastic to work long in such a position with little space for manoeuvre. This emphasizes the importance of considering also cognitive aspects, often considered secondary, in the design process.

VI. Ergonomic Validation of Observer Window Area

The objective of this case study was to carry out an ergonomic evaluation of the available spaces, the external visibility range through the bubble window and the reachability of the oxygen mask and the various control panel of the Observer Window Area (Fig.9). The area is characterised by the following components: Observer Window, Observer Table, Operator Seat, Oxygen Mask, Control Panels, Camera to take photographs or shots in operation, side window. This was a hybrid case study, since the operator shall perform some tasks in a seated position (as managing the camera) and others in a standing position (as surveillance mission at the bubble window).

A. Requirements identification

A valid solution for operators' comfort in terms of accommodation, reachability and verification of the spaces available was to be found and tested.

For the accommodation, the operators shall assume two main positions: rest and operating. In the rest position, the operator has the hands resting on the armrests of the seat that, starting from the neutral position, could also be moved. In the operating position, two configurations are possible. In the first configuration (Fig.10 left), the operator, starting from the sitting position, rests his hands on the Observer Table and balances slightly forward with the chest, to observe outside the bubble window. In the second configuration (Fig.10 right), the operator stands up, unbalancing the torso forward. For both the configurations, the adaptability of the various percentiles was to be tested, ensuring the perfect support of the feet on the ground. Furthermore, the reachability of all the main components (oxygen mask, camera and control panel) was to be ensured and the range of external visibility and the availability of the seats should be checked.

B. Input data collection

The following data were required for the study:

- bubble window footprint.
- console size.
- seat dimensions and range of movement relative to the SRP position.

C. Analysis of variables

Once the data and requirements have been finalised, the project variables have been identified. In order to design and evaluate alternative concepts, it was possible to:

1. Change the distance between the seat and the bubble window by changing the seat anchorage point for the same size and configuration of the two components.
2. Modify the footprint and configuration of the bubble window area, also intervening on bubble, Observer Table and control panel.
3. Change the size and range of the seat.

D. Virtual Verification

Objective assessment within Catia VR environment (Fig.11) has given positive results for all the percentiles tested. There were no issues about reachability and visibility, nor insufficient space for the DHMs of each tested percentage. Therefore, we moved on to validation within IC.IDO.

E. Ergonomic Validation within immersive environment

For the last step of the ergonomic assessment process, a real-time RULA analysis was conducted with the selected users, for each percentile. Users wore the full-body tracking equipment and acted naturally within the VR environment, simulating typical operations at the Observer Window Area. During all the test, RULA scores were registered, and mean values calculated for each percentile. Fig.13 shows the mean, maximum and minimum values of RULA scores. An example of the registered data is provided in Fig.12, representing one of the conducted tests for 5%ile female.

Unexpectedly, subjective measurements in immersive VE gave strongly negative results. Although all the users confirmed to be able to reach the required consoles, buttons, etc., they encountered significative visibility issues. For all the selected percentiles, the most critical action resulted to be looking out the bubble window, as it caused important stresses on upper arms, neck, and truck zones.

To confirm this, with reference to the RULA scoring system (Fig.2), the obtained mean values of RULA scores (Fig.13) imply a very high level of risk of MSD and require an immediate change to the current design of the Observer Window Area. Taking into account the identified variables in step *C.*, the iterative design of an alternative concept is currently underway. In particular, we are focusing on variable n.2 (Modify the footprint and configuration of the bubble window area, also intervening on bubble, Observer Table and control panel). Objective and subjective ergonomic evaluations will follow, as proposed by the methodology.

VII. Conclusion.

This work has proposed a human-centred methodology to support the ergonomic verification of a maritime patrol interiors' design, exploiting VR tools to include both objective and subjective measurements. The proposed methodology has been applied to the interiors' design evaluation of two areas of the MPA: Console Operator and Observer Window Area.

The adoption of both objective and subjective measurements has allowed to carry out a more complete ergonomic analysis of the tested concepts.

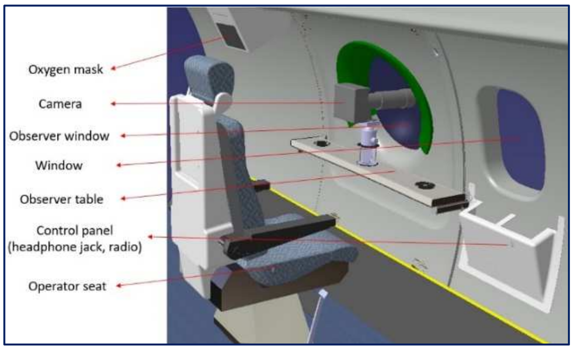

Fig. 9. Layout Observer Window area

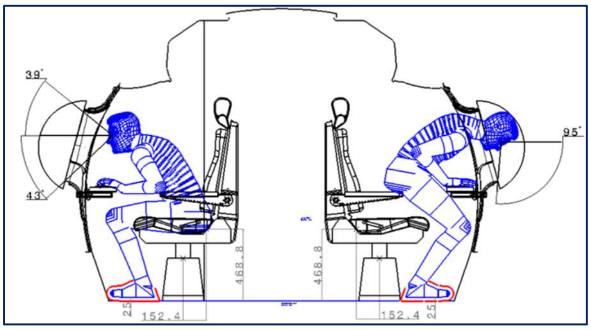

Fig. 10. Operators in the 2 operating positions at Observer Window Area

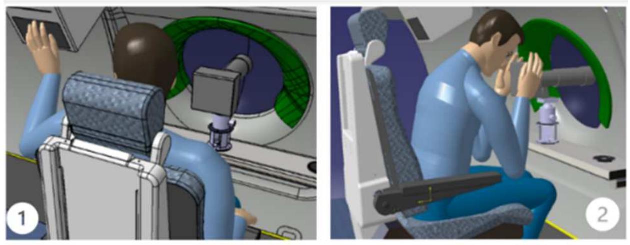

Fig. 11. Objective reachability evaluation with DHMs in working position at the Observer Window Area

As for Observer Window Area, the design configuration that seemed to offer satisfying levels of reachability, visibility and accommodability with objective measurements, unexpectedly resulted to require an immediate intervention in order to reduce an extremely high MSD risk for the operators. Furthermore, thanks to subjective assessment in immersive VR, it was discovered that the designed ergonomic configuration was considered unusable for the users, affirming that they would not feel comfortable to work in such workplace.

This work has demonstrated the strength and added value of the adoption of the proposed methodology based on the use of VR as a tool for ergonomic assessment, integrating both objective and subjective measurements. This methodology allows to collect crucial users' feedbacks before any physical prototype realization, allowing a significant reduction of time and money.

Acknowledgment

The authors are grateful to Leonardo S.p.A. for the case study.

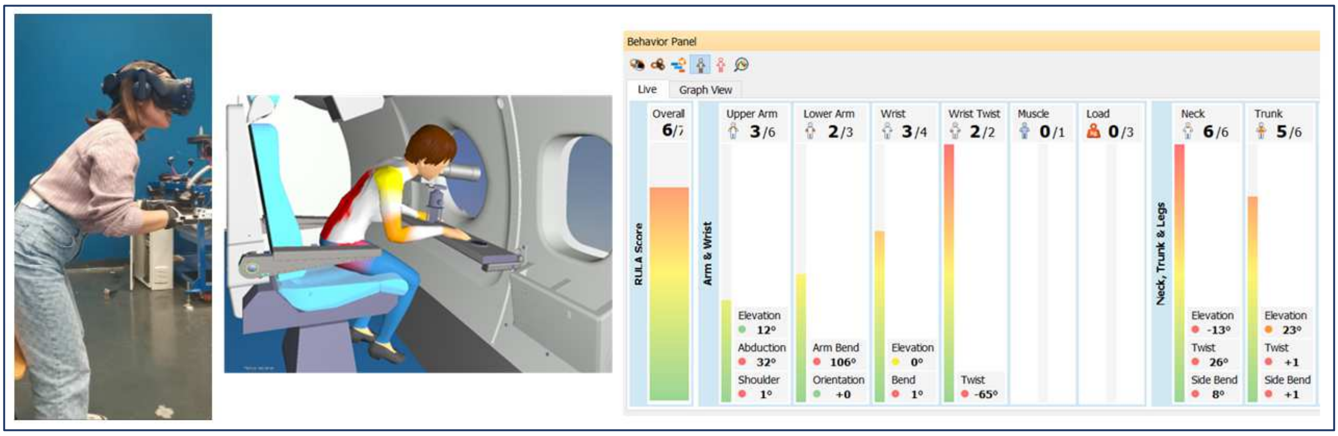

Fig. 12. Peak of detected RULA scores for 5%ile female at Observer Window Area

Percentiles	RULA scores		
	MIN	MAX	MEAN
5% Male	6	7	6,7
50% Male	5	7	6,3
95% Male	6	7	6,7
5% Female	6	7	6,3

Fig. 13. Min, max and mean RULA scores registered for all the percentiles at Observer Window Area

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